

Andreev reflection in Si-engineered Al/InGaAs hybrid junctions

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Abstract

Andreev-reflection dominated transport is demonstrated in Al/n-In_{0.38}Ga_{0.62}As superconductor-semiconductor junctions grown by molecular-beam epitaxy on GaAs(001). High junction transparency was achieved in low-doped devices by exploiting Si interface bilayers to suppress the native Schottky barrier. It is argued that this technique is ideally suited for the fabrication of ballistic transport hybrid microstructures.

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Superconductor-semiconductor (S-Sm) hybrid junctions are attracting increasing attention as their potential for the realization of exotic electronic-state and transport property configurations becomes more and more apparent [1,14,3]. In particular, merging ideas and techniques developed for semiconductor nanostructures with those of superconductivity research is proving extremely fruitful although several challenges still remain from the fabrication and theoretical standpoints.

Junction transparency is the key to access the novel transport regimes of interest. In particular, it is a crucial requirement for the observation of Andreev-reflection [4]. (In this process an electron injected from the Sm side condenses into a Cooper pair in the S part of the junction with the simultaneous retroreflection of a hole along the electron time-reversed path.) To achieve this high transparency different techniques have been explored including metal deposition immediately after As-decapping [5], Ar^+ back-sputtering [6], and *in situ* metallization in the molecular-beam epitaxy (MBE) chamber [7]. All these tests were performed in InAs-based S-Sm junctions where interface contamination is the main transparency-limiting factor. For the case of more established semiconductor materials (such as those grown on either GaAs or InP) the strongest limitation arises from the existence of a native Schottky barrier. Here, penetrating contacts [8,9] and heavily doped surface layers [5,10] were used to enhance junction transparency.

In a recent study we have reported on a new technique [11], alternative to doping, to obtain Schottky-barrier-free $\text{Al/n-In}_x\text{Ga}_{1-x}\text{As}(001)$ junctions ($x \gtrsim 0.3$) by MBE growth. This is based on the inclusion of an ultrathin Si interface layer under As flux which changes the pinning position of the Fermi level at the metal-semiconductor junction. This leads to the total suppression of the Schottky barrier. In this Letter we demonstrate that this technique can be successfully employed to achieve high transparency in MBE-grown S-Sm hybrid junctions involving low-doped and low-In-content InGaAs alloys that are ideal candidates for the implementation of ballistic-transport structures.

$\text{Al/n-In}_{0.38}\text{Ga}_{0.62}\text{As}$ S-Sm junctions incorporating Si interface layers were grown by MBE at the TASC-INFM facility. Their schematic structure is shown in Fig. 1. The semicon-

ductor portion consists of a 300-nm-thick GaAs buffer layer grown at 600 °C on n-type GaAs(001) and Si-doped at $n \sim 10^{18} \text{ cm}^{-3}$ followed by a 2- μm -thick n-In_{0.38}Ga_{0.62}As layer grown at 500 °C with an inhomogeneous doping profile. The top 1.5- μm -thick region was doped at $n = 6.5 \cdot 10^{16} \text{ cm}^{-3}$, the bottom buffer region (0.5 μm thick) was heavily doped at $n \sim 10^{18} \text{ cm}^{-3}$. After In_{0.38}Ga_{0.62}As growth the substrate temperature was lowered to 300°C and a Si atomic bilayer was deposited under As flux [11]. Al deposition was carried out *in situ* at room temperature.

Rectangular 100×160 μm^2 Al/n-In_{0.38}Ga_{0.62}As junctions were patterned on the sample surface using standard photolithographic techniques and wet chemical etching. Two additional 100×50 μm^2 -wide and 200-nm-thick Au pads were electron-beam evaporated just on top of every Al pattern in order to allow four-wire electrical measurements. The sample was mounted on a non magnetic dual-in-line sample holder, and 25- μm -thick gold wires were connected to the gold pads by standard ultrasonic bonding technique. Current-voltage (I-V) characterizations as a function of temperature (T) and static magnetic field (H) were performed in a ³He closed-cycle cryostat.

The critical temperature (T_c) of the Al film was measured to be 1.1 K, which corresponds to a superconducting gap $\Delta \approx 0.16 \text{ meV}$. The normal-state resistance R_N of our devices was 0.2 Ω , including the series-resistance contribution ($\approx 0.1\Omega$) of the semiconductor. At $H = 0$ and below T_c , dc I-V characteristics exhibited important deviations from linearity around zero bias. These features can be better analyzed by plotting the differential conductance (G) as a function of the applied bias (V). In Fig. 2 we show a typical set of G -*vs*- V curves obtained at different temperatures in the 0.33–1.03 K range. These data clearly show that the transport properties of our system are quite unlike those of a S-Sm tunnel junction. In fact even at $T = 0.33 \text{ K}$, i.e. well below T_c , a high value of G is observed at zero bias. At such low temperatures and at low bias (i.e., when the voltage drop across the junction is lower than Δ/e [12]), transport is dominated by Andreev reflection. The observation of such pronounced Andreev reflection demonstrates high junction transparency. The latter can be quantified in terms of a dimensionless parameter Z according to the Blonder-Tinkham-

Klapwijk (BTK) model [16] (in this model Z is related to the normal-state transmission coefficient t by $t = (1 + Z^2)^{-1}$). This approach was developed in the context of ballistic systems, but has been widely applied to diffusive systems (like the present one) in order to gain an estimate of the junction transmissivity [8,10,13,14]. To analyze the data of Fig. 2 we followed the model by Chaudhuri and Bagwell [15], which is the three-dimensional generalization of the BTK model. For our S-Sm junction we found $Z \approx 1$ corresponding to a $\sim 50\%$ normal-state transmission coefficient. We note that without the aid of the Si-interface-layer technique, doping concentrations over two orders of magnitude greater than that employed here would be necessary to achieve comparable transmissivity (see e.g. Refs. [5,8,10]). This drastic reduction in the needed impurity concentration is a very attractive feature for the fabrication of ballistic structures. It should also be noted that our reported Z value is close to the intrinsic transmissivity limit related to the Fermi-velocity mismatch between Al and InGaAs [17].

We should also like to comment on the homogeneity of our junctions. Our estimate of Z leads to a theoretical value of the normal-state resistance R_N^{th} which is much smaller than the experimental value R_N^{exp} : $R_N^{th}/R_N^{exp} = 0.003$. This suggests that only a small fraction (R_N^{th}/R_N^{exp}) of the contact area has the high transparency and dominates the transport properties of the junction, as already reported by other authors with different fabrication techniques [8,13]. Values of R_N^{th}/R_N^{exp} ranging from $\sim 10^{-4}$ to $\sim 10^{-2}$ can be found in the literature (see, e.g., Refs. [5,8,13]).

Such inhomogeneities, however, are not perceptible on the lateral length scale of our contacts and we observed a high uniformity in the transport properties of all junctions studied.

The superconducting nature of the conductance dip for $|V| < \Delta/e$ is proved by its pronounced dependence on temperature and magnetic field. Figure 2 shows how the zero-bias differential-conductance dip observed at $T = 0.33$ K progressively weakens for T approaching T_c . This fact is consistent with the well-known temperature-induced suppression of the superconducting energy gap Δ . Far from $V = 0$ the conductance is only marginally affected

by temperature as expected for a S-Sm junction when $|V|$ is significantly larger than Δ/e [16]. A small depression in the zero-bias conductance is still observed at $T \simeq T_c$. This, together with the slight asymmetry in the G -vs- V curves, can be linked to a residual barrier at the buried InGaAs/GaAs heterojunction.

In Fig. 3 we show how the conductance can be strongly modified by very weak magnetic fields (H) applied perpendicularly to the plane of the junction. The G -vs- V curves shown in Fig. 3 were taken at $T = 0.33$ K for different values of H in the 0–5 mT range. The superconducting gap vanishes for H approaching the critical field (H_c) of the Al film ($H_c \simeq 10$ mT at $T = 0.33$ K). Consequently, the zero-bias conductance dip is less and less pronounced and at the same time shrinks with increasing magnetic field. The latter effect was not as noticeable in Fig. 2 owing to the temperature-induced broadening of single-particle Fermi distribution function [16].

In conclusion, we have reported on Andreev-reflection dominated transport in MBE-grown Si-engineered Al/n-In_{0.38}Ga_{0.62}As hybrid junctions. Transport properties were studied as a function of temperature and magnetic field and showed junction transmissivity close to the theoretical limit for the S-Sm combination. The present study demonstrates that the Si-interface-layer technique is a promising tool to obtain high-transparency S-Sm junctions involving InGaAs alloys with low In content and low doping concentration. This technique yields Schottky-barrier-free junctions without using InAs-based heterostructures and can be exploited in the most widespread MBE systems. It is particularly suitable for the realization of low-dimensional S-InGaAs hybrid systems grown on GaAs or InP substrates. We should finally like to stress that its application in principle is not limited to Al metallizations and other superconductors could be equivalently used. In fact, to date the most convincing interpretation of the silicon-assisted Schottky-barrier engineering is based upon the heterovalency-induced IV/III-V local interface dipole [18]. Within this description Schottky-barrier tuning is a metal-independent effect.

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FIGURES

FIG. 1. Schematic structure of the Al/n-In_{0.38}Ga_{0.62}As junctions studied in this work. Further details are given in the text.

FIG. 2. Differential conductance *vs* bias voltage of a Si-engineered Al/n-In_{0.38}Ga_{0.62}As single junction. The four curves shown were obtained at zero magnetic field and temperatures in the 0.33–1.03 K range.

FIG. 3. Differential conductance *vs* bias voltage of a Si-engineered Al/n-In_{0.38}Ga_{0.62}As single junction. The four curves shown were obtained at $T = 0.33$ K under different magnetic fields perpendicular to the junction plane.





